PORTLAND HARBOR RI/FS

APPENDIX H

EPA REVIEW OF EXISTING AND HYDRODYNAMIC AND SEDIMENT TRANSPORT MODEL

FEASIBILITY STUDY

June 2016

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H1. REVIEW OF EXISTING HYDRODYNAMIC AND SEDIMENT TRANSPORT MODEL

The draft Portland Harbor FS included a hydrodynamic and sediment transport (HST) model of the lower Willamette River downstream of RM 13 to the confluence with the Columbia River. The primary purpose of the model was to evaluate remedial alternatives, support FS level cap armoring design and evaluate the potential for erosion of buried sediment contamination.

EPA engaged with the LWG throughout the development of the HST model with support from the U.S. Army Corps of Engineers Engineer Research and Development Center (ERDC). This process repeatedly identified a number of shortcomings that preclude its use to predict future changes in sediment concentrations at the Site. A summary of EPA's engagement is summarized below:

- 2004: Review of the initial development of the hydrodynamic model for the lower Willamette River. The failure to include a long reach of the Columbia River was identified as the most significant issue.

- 2005: Review of the second version of the hydrodynamic model and first version of the sediment transport model. Issues identified included the use of SEDFLUME data, and that the reach of the Columbia River added to the grid was too short, resulting in extrapolation of long distances from gaging stations to the boundary conditions.

- 2009: Participated in LWG presentations of the revised sediment transport model that used a version of the SEDZLJ sediment bed model, and identified issues that required the LWG to perform additional analysis and model simulations. Further discussions of the additional analysis and model simulations occurred in the fall of 2009. No model approval was given as the model was not fully calibrated or validated at that time.

- 2010: Additional discussions between EPA and the LWG regarding unresolved issues with the HST model. The modeling approach was presented in a May 2010 presentation. In July 2010, EPA authorized the LWG to go forward with the model.

- 2012: The HST model was submitted along with the draft FS. In its December 2012 comments on the draft FS, EPA identified a number of shortcomings with the model and the evaluation of MNR. Key shortcomings identified by EPA included:

    - The failure to properly link the sediment transport model with hydrodynamic model. This shortcoming in the model framework resulted in the over prediction of deposition (and hence MNR through deposition) in some portions of the River. EPA noted that this omission of a fundamental principle of hydrodynamics and sediment transport in the modeling framework greatly reduces the confidence in MNR predictions.

- At EPA's request, the LWG provided the HST model to ERDC, which performed a detailed review and diagnostic analysis. Further analysis using a linked version of the modeling framework conducted by ERDC indicated that the FS model predicted greater deposition than the linked model (defined as greater than 0.5 ft) in 55 percent of the model grid cells, with results ranging from 6 inches to greater than 20 feet more deposition. The evaluation also indicated that the linked and unlinked models show similar deposition (+/- 0.5 ft) in 40 percent of the cells and the FS model showed less deposition (or greater scour) than the linked version of EFDC in 5 percent of the cells. This evaluation demonstrated a strong bias for greater deposition by the MNR model used in the FS.

- The effectiveness of MNR was evaluated on an inappropriate spatial scale. Many of the empirical lines of evidence used to evaluate MNR are overly generalized and may not hold true on smaller scales. For example, the HST model concluded that the harbor is "net depositional" based on averages for the site as a whole. However, the spatial and temporal patterns of erosion and deposition in localized areas of sediment contamination are critical to predicting future sediment concentrations. Monitoring of sediment elevations between 2003 and 2009 indicates that many of the highly contaminated areas, including along the banks, are net erosional. The one river mile reach scale is too coarse to be meaningful. For example, between RM 11 and 11.8, the analysis concludes that this reach is generally not likely to recover. However, there are significant differences between the east and west sides of the river due to anthropogenic effects such as dredging and propwash. As a result, the west side of the river is likely to recover more quickly than the east side. Similarly, although the draft FS report noted the variability of MNR effectiveness between RM 5 and 6. This variability was not taken into account in the evaluation of MNR effectiveness

- The effectiveness of MNR did not fully take into account wind and wake wave generated erosion. EPA noted that wind and wake driven waves are likely to be significant given that seasonal changes in river elevation will tend to expose a significant bank zone to waves of sufficient strength to generate erosional forces that must be considered in the FS.

- Erosion of contaminated material may occur even when limited changes in sediment bed elevation are observed or predicted due to initial erosion of the sediment bed during high flow events followed by subsequent deposition as currents slow and material drops out of suspension.

  - Erosion was not evaluated on a small-scale area. Erodibility parameters utilized in the model were averaged over the whole Site for cohesive bed areas. Therefore, in the places with above average erodibility, the model will erroneously predict no erosion at some times.

- 2013: Further discussions between EPA and the LWG regarding the findings of the ERDC review. LWG presented limited results from a quasi-linked HST modeling they performed.
- 2014: EPA commissioned an independent review of the LWG HST model by Portland State University.
- 2014: ERDC review of the independent review by Portland State University.
- 2015 – ERDC initiated the development of a new HST model.
- 2016 – EPA's National Remedy Review Board and Contaminated Sediments Technical Advisory Group review of the Portland Harbor conceptual remedy identified several of the model limitations discussed in this appendix, and noted that the "Willamette River poses unique model development challenges and that, at this time, the Region is not relying on a model to predict various aspects of hydrodynamics, sediment transport, food chain/bioaccumulation and sediment deposition" and agreed that a remedy could be selected without completing additional modeling.

Based on the additional evaluations conducted by Portland State University and ERDC, a number of additional shortcomings in the modeling approach have been identified. Key shortcomings are summarized below:

The extent the model domain extends into the Columbia River
The current model grid extends into the Columbia River approximately 1,000 feet up and downstream of the confluence with the Willamette River. In order to correctly model surface water and sediment transport at the confluence of the Willamette and Columbia Rivers or to model the condition in which the Columbia River backs up into the Willamette River, the model domain should extend to a point near the confluence of the Columbia River and Multnomah Channel near St. Helens, Oregon.

Failure to consider bedload transport
The physical CSM for the lower Willamette River presented in the Revised Phase 2 Recalibration Results (West Consultants and Tetra Tech, Inc., 2009) emphasizes the importance of bedload transport and notes that approximately half the sediment transport from upstream into the Study Area (RM 1.0 to 11.8) occurs via bedload, and notes that a downstream decrease in bedload is important to deposition in the Study

Area. Due to the importance of bedload induced sediment deposition within the Site to natural recovery processes, the failure to incorporate bedload into the HST model is a major omission that calls into question all results based on the sediment transport modeling.

Failure to consider rain-on-snow winter flooding

These types of floods are particularly important because flows rise rapidly and the supply of fine sediment from upriver is large, leading to the potential for erosion (and downstream export) followed by deposition. The Willamette River typically rises faster than the Columbia River. However, the erosion potential of some winter floods is probably reduced by Columbia River flow management that causes artificially high water levels. Moreover, the fine sediment supply associated with rain-on-snow floods may differ from that which occurs under other conditions.

Failure to properly evaluate a 100-flood event

The model did not properly model a 100-year flow event. Historical data indicates that at 100-year flood volume of 500,000 cfs is realistic. The current model simulated the 1996 flood event which is approximately a 425,000 cfs event.

Model grid and aspect ratio

The current model used a grid size of 200 m by 25 m, which equates to an aspect ratio of 8. Large aspect ratios are sometimes associated with poor numerical properties. In addition, a 200 m long grid cell is likely to include variable depths and possibly not represent processes well. The effect of large aspect ratios for some of the grid cells on the numerical solution is well known, but has not been quantified for this modeling study. In addition, the use of larger grid cells resulted in more numerical dispersion in the approximate solutions to the discrete difference equations used in the model. Finally, the grid resolution utilized in the model limits the accuracy of mapping of some remedial alternatives onto the model thus decreasing the accuracy of related simulations associated with the evaluation of remedial alternatives in the FS.

Model Calibration

The model has not been appropriately calibrated. Separate calibration and analysis periods are needed to fully validate the Environmental Fluid Dynamics Code (EFDC) circulation modeling, with each period being at least a year long and encompassing both flood periods and low-flows. At a minimum, a subset of the longer validation time period should have been used to calibrate and validate the hydrodynamic model.

Sediment Loading

The model did not appropriately consider sediment loading. Sediment supply from the Willamette River is a vital boundary condition for the sediment transport and fate and transport models. Only post-1973 USGS sediment concentration and load data for the Willamette River were used, with observations for days with flows up to approximately 200,000 cfs. These data do not include the available larger 1962-1965 daily data set that includes detailed observations for the December 1964 flood, including multiple observations on the days of peak sediment load. The 1964 flood exhibited a peak flow of approximately 443,000 cfs and is one of the four largest Willamette River flood events of the last century. Accordingly, the 1962-1965 data set is an important resource that should have been used. This data set also provides percent sand data, so that the sediment load can be correctly divided into sand and fines transport, and the fines load needs to be divided into silt and clay inputs. Additional problems noted with the sediment loading analysis include:

- Hysteresis effects: The rating curves did not consider sediment load hysteresis, though this is an important factor in the system. Typically, the sediment load is highest on the rising arm of the freshet, which is an important feature of rain-on-snow floods.

- Sediment quality: The modeled division of the supply between fines and sand is incorrect for high flows, in part because it did not consider the very large supply of clay material, which is likely most prominent during rain on snow floods.

- Lower Willamette River deposition and erosion: The sediment load measured at the Morrison Street Bridge does not represent the load to the lower Willamette River because those measurements are affected by deposition and erosion between Oregon City and Portland Harbor. It is likely that the load during low-flow (depositional) periods is underestimated, while the load during high flow periods may be overestimated. The correct use of the Morrison Street Bridge data and rating curve is for validation of the model predictions, not as a boundary condition, because the sampling is within the system rather than at the boundary. This problem can only be remedied after collection of an appropriate data set at Oregon City.

- Columbia River sediment loading: The Columbia River sediment load at Vancouver was set based on 1963-1969 data. While a reasonable first step, the percent sand was underestimated. Information in Haushild et al. (1966) should be used to set the percent sand as a function of flow. Also, post 1973 USGS NWIS should have been used, as was done for the Morrison Street Bridge.

Settling velocities are inappropriately represented
The combined silt and clay size class settling velocity was given by

$$W_s\ (m/day) = 3.3(C_1 G)^{0.12} \qquad \text{Equation H1-1}$$

where G is the water column shear stress (dyne/cm^2), and C_1 is concentration of size class 1 (mg/L). Horizontal gradients in shear are high in Portland Harbor, especially during high flow periods. Thus, as a parcel of water moves, the settling velocity (W_S) of its load may vary. In systems with large spatial scales and slow motions (such as lakes and reservoirs), particles will have time to adjust to their changing environment, which likely represents equilibrium behavior. This assumption may not be the case in Portland

Harbor and may not be appropriate. Unrealistic results may occur during both high-flow periods and in times and places where tidal currents reverse, because shear will change rapidly in both cases.

Horizontal gradients in C_1 have not been estimated for Portland Harbor, but the same issue applies to these gradients as to shear gradients. Equation H1-1 is unrealistic if the predicted values of W_S change more rapidly than the particle field actually responds due to advection to a different environment.

The water column shear stress (G) is intended to be a water-column value, but bed skin friction shear stress τ_{SF} is used instead. If the flow is approximately a channel shear flow, then the shear varies linearly with depth, being maximum at the bed surface and zero at the free surface (unless there is wind). Use of τ_{SF}, which is a component of the bed stress, may under- or over-estimate water column shear stress.

During periods of weak river flow, currents reverse in Portland Harbor, and sediments typically settle to the bed during periods of slack water. The W_S formulation shown in Equation H1-1 prevents this from happening by taking W_S to zero as the current approaches slack. This is clearly unrealistic.

Hydrodynamics and sediment transport are not properly linked

The EFDC hydrodynamic model and the SEDZLJ sediment transport model are not coupled to allow changes in bed elevation (due to deposition and erosion) predicted by SEDZLJ to be used to update the flow field predicted by the hydrodynamic model during the next time step. Under some circumstances, e.g., in water bodies with minimal morphologic changes over the period of model simulation, this will not cause major problems in the modeling, and it is a useful simplification for long simulations. However, erosion of up to 1 m during severe flood events may occur, resulting in a change in the hydrodynamics. In addition, the uncoupled model used resulted in unrealistic amounts of deposition in certain reaches of the river since the decrease in the flow depths caused by the predicted increase in bed elevations in these depositional areas was not reflected in the hydrodynamic model. The impacts of this simplification to the model framework should be judged using fully coupled runs for comparison. Impacts of this simplification also need to be considered in sensitivity analyses. The impact of this simplified model framework on the results from the contaminant transport and fate model also needs to be fully evaluated.

Underestimation of uncertainty in the model

While the sensitivity analysis recognized the importance of sediment loading, no other sources of uncertainty and bias associated with the hydrodynamic and sediment transport modeling were recognized. The result is that uncertainties are far higher than reported.

Improper model validation

The validation of the sediment transport model rested entirely on attempts to reproduce observed 2003 to 2009 erosion and deposition patterns, a time period without a major flood. This approach is inherently ambiguous and incomplete. It is not possible to know whether the right answer has been reached for the wrong reasons, even if the bed changes are plausible for this time period. For example, if a model and data agree that an area shows no net erosion or deposition over a time period, this does not make the model correct, because erosion and deposition cycles and events that profoundly affect contaminant transport may not have been modeled correctly. Further, as noted above, the Willamette River sediment load is incorrectly considered and bedload transport has been neglected. Thus, it is likely that the model's success is based on incorrect parameterizations, calling into question its predictive ability.

Given the difficulties documented above in the hydrodynamic and sediment transport models, it is vital that SEDZLJ water column transport predictions be tested against measured data. While further data collection is needed, there are readily available data sets that have not been used, such as the 2009-2014 USGS time series of turbidity at the Morrison Street Bridge. Acoustic backscatter data or ABS (better for coarser sizes) and side-looking acoustic Doppler current profiler (ADCP) data could be obtained from the Morrison Bridge gauging station. Both time series should be calibrated, considering variations in both particle size and concentration.

H2. EVALUATION OF PREDICTED VS. MEASURED CHANGES IN SEDIMENT BED ELEVATION

A key element of the long-predictions of reductions in contaminant concentrations associated with natural recovery processes is the deposition of cleaner material resulting in declines in sediment concentrations. To further evaluate the ability of the HST model to accurately predict sediment deposition and erosion, a comparison of predicted vs. measured changes in bathymetry was performed on an SDU basis.

The overall approach involved comparing measured changes in sediment bed elevation to predicted changes for each model grid cell. Conducting the evaluation on a grid cell basis facilitates comparison of predicted and measured changes in bathymetry. The first step in the process was to assign sediment bed elevations from the various bathymetric surveys to each model grid cell. Sediment bed elevations calculated on a 10 ft by 10 ft GIS pixel scale were averaged over the area of each model grid cell to complete this conversion. Each model grid cell represents approximately one acre (the mean grid cell area is 1.1 acres), For example, the bed elevations in approximately 479 pixels were averaged to determine the average bed elevation in a grid cell with a 1.1 acre area. SDUs range between 50 and 100 acres in size.

Measured changes in bathymetry were calculated using the results of the five bathymetric surveys conducted within Portland Harbor between 2002 and 2009: January 2002, July/September 2002, May 2003, February 2004, and January 2009. Measured changes in bathymetry were calculated for each possible survey pair. Based on the five surveys, 10 survey pairs are possible:

S5-S1, S5-S2, S5-S3, S5-S4, S4-S1, S4-S2, S4-S3, S3-S1, S3-S2, S2-S1

Where:

S1 = January 2002
S2 = July/September 2002
S3 = May 2003
S4 = February 2004
S5 = January 2009

Measured changes in bathymetry were compared to modeled changes for the same time period. Changes in bathymetry were compared relative to the average elevation for each model grid using the approximate time mid-point of the surveys above (Year 0), where model output represents change from year 0.

Comparisons between measured and predicted changes in sediment bed elevation were performed on a fate and transport model grid cell basis. Grid cells were assigned to sediment decision units and plotted to compare predicted changes in sediment bed elevation with measured sediment bed elevation for each of the ten possible bathymetric survey pairs per SDU (**Figure H2-1)**. A one to one line was provided for each plot. Points above the line indicate that the model is over predicting changes in sediment bed elevation, points below the line indicate that the model is under predicting changes in sediment bed elevation. In addition to the 1:1 line, the results can also be classified based on quadrant with the center point being 0,0 (no predicted change in sediment bed elevation; no measured change in sediment bed elevation):

Upper Left Quadrant Model Prediction = Deposition Measured Results = Erosion	Upper Right Quadrant Model Prediction = Deposition Measured Results = Deposition
Lower Left Quadrant Model Prediction = Erosion Measured Results = Erosion	Lower Right Quadrant Model Prediction = Erosion Measured Results = Deposition

This evaluation indicates that the model predicts deposition the majority of the time. Erosion is predicted only within SDUs RM 5.5E, RM 6.5E, RM11E and RM6 Nav. However, measured changes in bathymetry indicate that some erosion was observed within every SDU. In addition, the plots did not correlate well with the 1:1 line which would indicate a good correlation between predicted and measured changes in sediment bed elevation. Adjusted r^2 values range from 0.0028 to 0.42 with an average r^2 of 0.093. SDU RM 2E ($r^2 = 0.42$) and RM 3.9W ($r^2 = 0.38$) exhibited the best correlation between measured and modeled results. Although deposition is under-predicted in some SDUs as evidenced by a greater number of points below the 1:1 line (RM 2E, Swan Island, RM 3.9W, RM 5W, RM 6W, RM 6NAV, and RM 7W), this is a result of the magnitude of the predicted deposition in comparison to the magnitude of the measured deposition. Only in SDUs RM 5.5E, RM 6.5E, RM 11E and RM 6Nav does the model predict erosion when deposition is observed (lower right quadrant). Conversely, the model predicts deposition when erosion is observed in every SDU.

These conclusions are supported by the positive and negative predicted values included **Figure H2-1**. Positive predictive values measures the percentage of positive predictions for which there actually was a positive response. In this case, the evaluation considers the percentage of time deposition was predicted when deposition was measured. Positive predictive values are greater than 50 percent - ranging from 57 percent to 97 percent - for all SDUs. However, the negative predictive power – which measures the percentage of time erosion was predicted when erosion was measured - is below 50 percent for all SDUs, with a maximum negative predictive value of 33 percent in SDU RM6Nav. As noted above, because the model failed to predict erosion in all but four of the SDUs, negative predictive values can only be calculated for 4 SDUs.

Overall, the results of this analysis suggest that the Portland Harbor HST model tends to over predict deposition, particularly in areas where erosion is measured. As a result, the utility of the contaminant fate and transport model developed for the Site to evaluate MNR is limited.

H3. REFERENCES

WEST Consultants and TetraTech, 2009. Revised Phase 2 Recalibration Results: Hydrodynamic Sedimentation Modeling for Lower Willamette River. Draft Report. Prepared for Lower Willamette Group, Portland, OR.

Haushild, W. L., R. W. Perkins, H. H. Stevens, G. R. Dempster, and J. L. Glenn, 1966. *Progress report: radionuclide transport in the Pasco to Vancouver, Washington reach of the Columbia River July 1962 to September 1963*. Portland, Oregon, U. S. Geological Survey. 188 p. (Prepared in co-operation with the U. S. Atomic Energy Commission.)

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Figures

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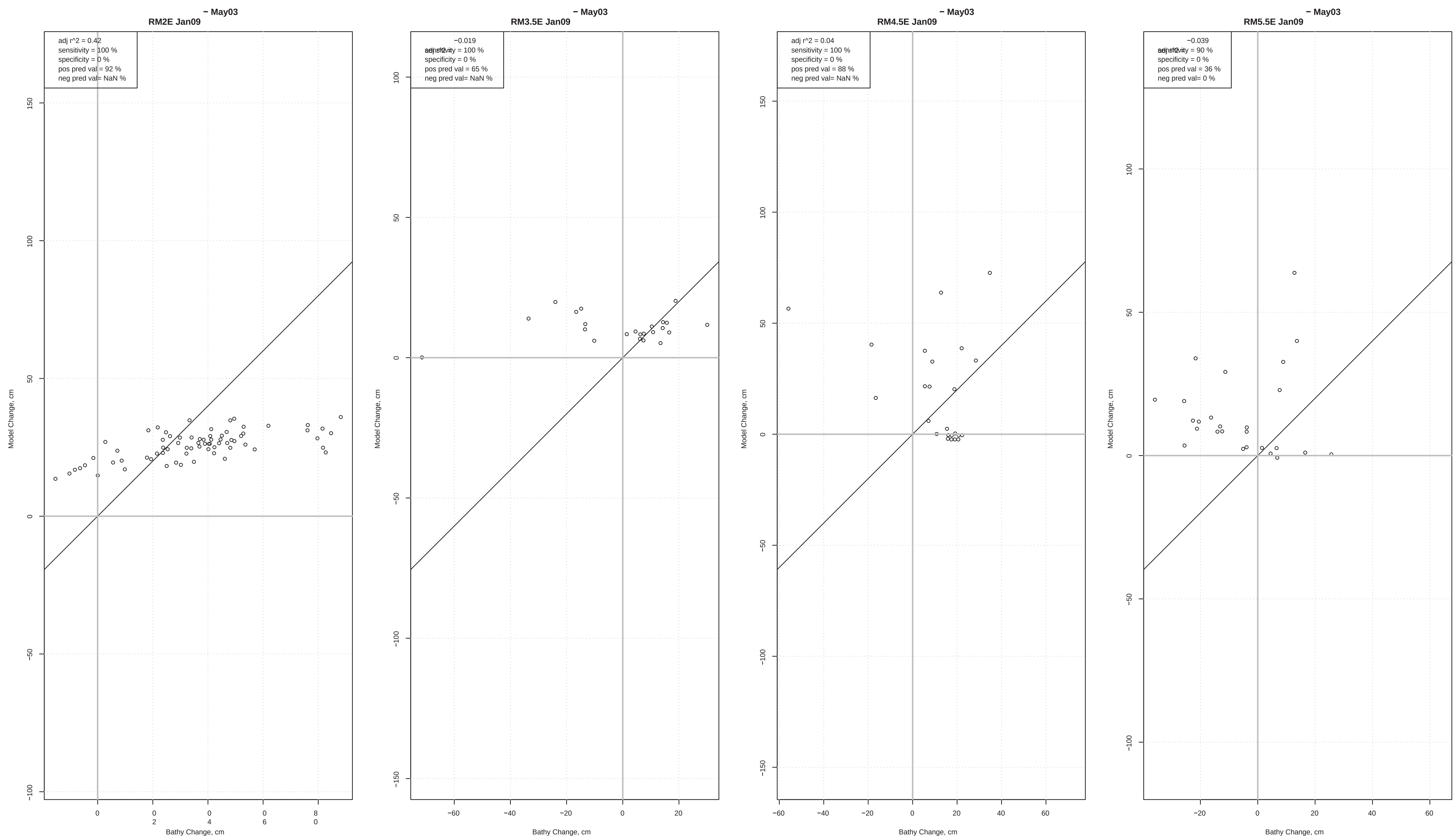

Figure H2-1a. Comparison of Measured and Predicted Changes in Sediment Bed Elevation on a SDU Basis

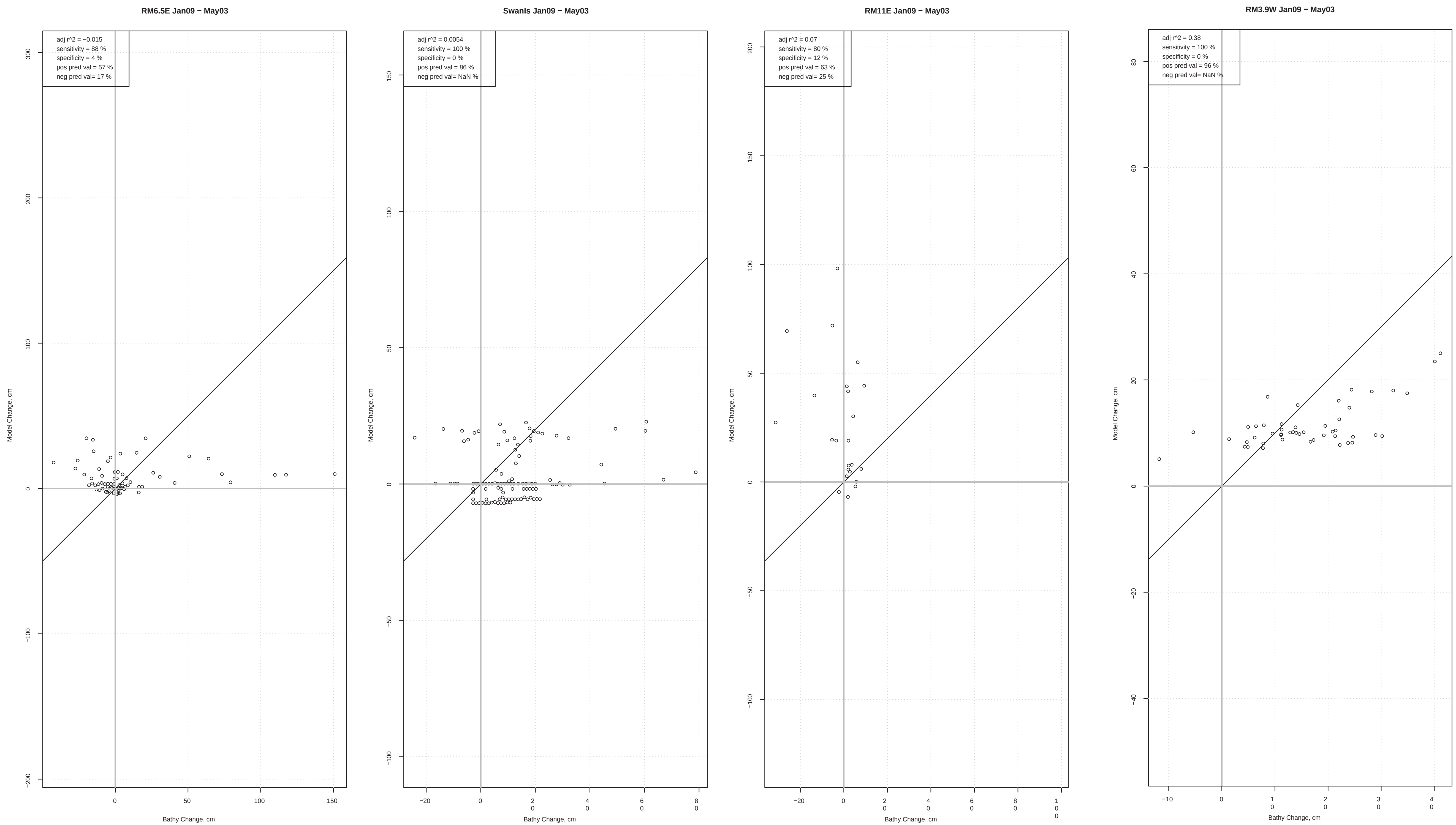

Figure H2-1b. Comparison of Measured and Predicted Changes in Sediment Bed Elevation on a SDU Basis

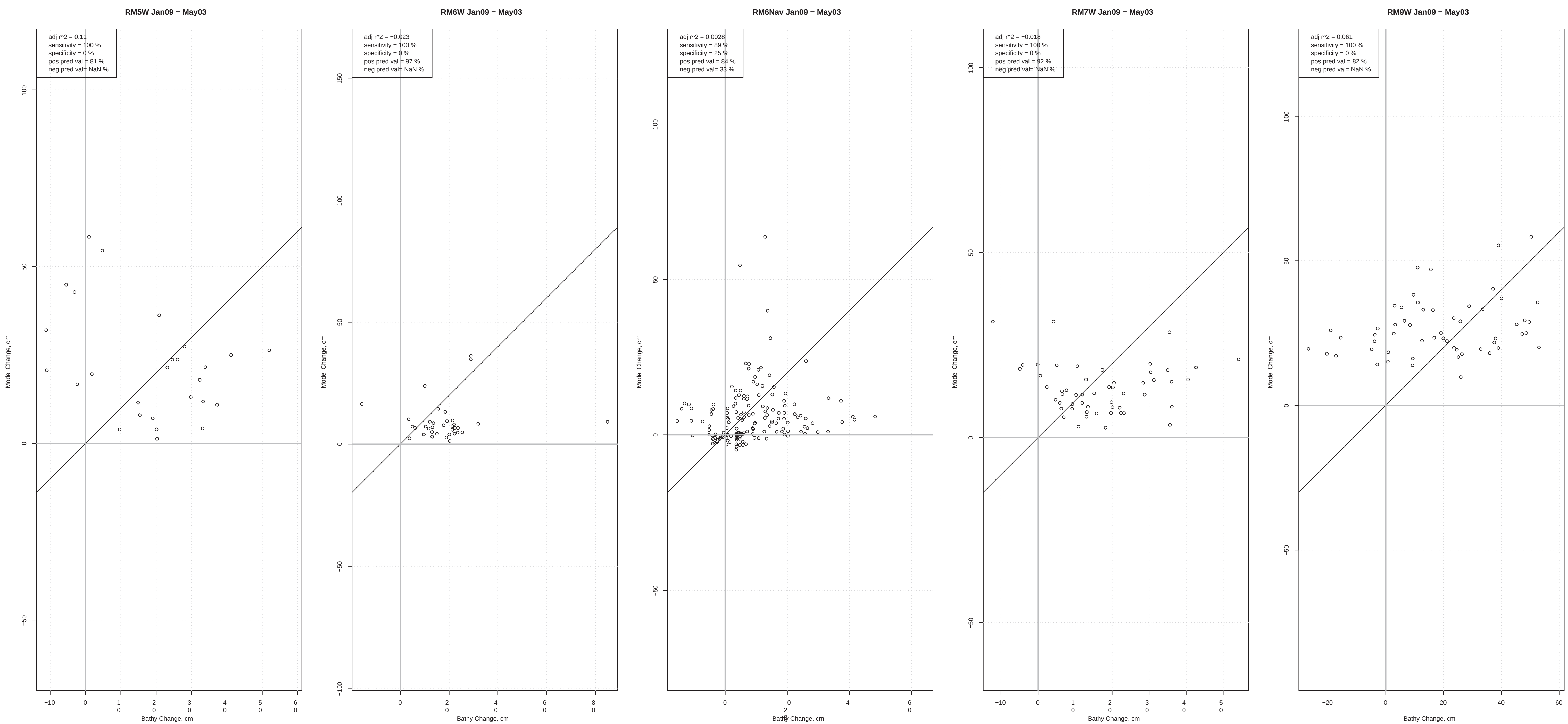

Figure H2-1c. Comparison of Measured and Predicted Changes in Sediment Bed Elevation on a SDU Basis